Sizes
Tilts and Obliquities

Offset Tilted Dipole (poor) Approximation
Multipole coefficients / Dipole
Indicates degree of complexity

Stanley &
Bloxham
2006
• Did Moon ever have dynamo?
• Mars' dynamo died >3.5 BYA.
Bow Shock:
• Kinetic energy $\rightarrow$ thermal energy
• Flow diverted around obstacle
• $\sim11\%$ less pressure at MP than in upstream SW
**Mercury:** Extreme solar wind conditions -> exposed planet

*Slavin et al.* 2010

**Mars:** Weak, irregular field -> bumpy surface + changing topology

*David Brain*
SW ram pressure <=> internal magnetic field pressure

\[ \rho_{sw} V_{sw}^2 = B_o^2 \frac{(R_p/r)^6}{2\mu_o} \]

BUT what about currents at the magnetopause?  \( \rightarrow 2B_{\text{dipole}} \)

\[ \rho_{sw} V_{sw}^2 = (2B_o)^2 \frac{(R_p/r)^6}{2\mu_o} \]

Solve for \( r \Rightarrow R_{\text{MP}} \)

\[
\frac{R_{\text{MP}}}{R_{\text{planet}}} = 2^{1/3} \left[ \frac{B_o^2}{2\mu_o \rho_{sw} V_{sw}^2} \right]^{1/6}
\]
Yes, I am being a bit sloppy here...

For more comprehensive treatment of magnetosheath, magnetopause (including details of the history) see 2012 HSS lecture by John Dorelli.

http://www.vsp.ucar.edu/Heliophysics/pdf/
DorelliTerrestrialMagnetosphere.pdf

And lecture from 2011 from Toffoletto

I am keen to compare planetary magnetospheres – and comparison with Earth.
Dipole Magnetic Field in Solar Wind

SW Ram Pressure $\leftrightarrow$ Magnetic Pressure

\[ \frac{R_{MP}}{R_{\text{planet}}} \sim 1.2 \left[ \frac{B_o^2}{2\mu_0 \rho_{sw} V_{sw}^2} \right]^{1/6} \]

Chapman-Ferraro Distance
\[ \frac{R_{CF}}{R_p} \sim 1.2 \left\{ \frac{B_0^2}{(2 \mu_0 \rho_{sw} V_{sw}^2)} \right\}^{1/6} \]

Quick chat with your neighbors....

- How does \( \rho_{sw} \) vary with distance from Sun? \( \sim 1/D^2 \)
- How does \( V_{sw} \) vary with distance from Sun? \( \sim \text{constant} \)
- How does \( \left\{1/\rho_{sw} V_{sw}^2 \right\}^{1/6} \) vary with distance? \( \sim D^{1/3} \)
\[ \frac{R_{CF}}{R_p} \sim 1.2 \left\{ \frac{B_o^2}{2 \mu_0 \rho_{sw}} V_{sw}^2 \right\}^{1/6} \]

<table>
<thead>
<tr>
<th></th>
<th>Mercury</th>
<th>Earth</th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_o ) Gauss</td>
<td>.003</td>
<td>.31</td>
<td>4.28</td>
<td>.22</td>
<td>.23</td>
<td>.14</td>
</tr>
<tr>
<td>( \frac{R_{CF}}{R_M} ) Calc.</td>
<td>1.4 ( R_M )</td>
<td>10 ( R_E )</td>
<td>46 ( R_J )</td>
<td>20 ( R_S )</td>
<td>25 ( R_U )</td>
<td>24 ( R_N )</td>
</tr>
<tr>
<td>( R_M ) Obs.</td>
<td>1.4-1.6 ( R_M )</td>
<td>8-12 ( R_E )</td>
<td>63-92 ( R_J )</td>
<td>22-27 ( R_S )</td>
<td>18 ( R_U )</td>
<td>23-26 ( R_N )</td>
</tr>
</tbody>
</table>
Magnetospheres scaled by stand-off distance of dipole field

<table>
<thead>
<tr>
<th></th>
<th>$M/M_\oplus$</th>
<th>$M_{\text{Dipole}}$</th>
<th>$M_{\text{mean}}$</th>
<th>$M_{\text{Range}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>$\sim 8 \times 10^{-3}$</td>
<td>1.4 $R_M$</td>
<td>1.4 $R_M$</td>
<td></td>
</tr>
<tr>
<td>Earth</td>
<td>1</td>
<td>$10 R_E$</td>
<td>$10 R_E$</td>
<td></td>
</tr>
<tr>
<td>Saturn</td>
<td>600</td>
<td>$20 R_S$</td>
<td>$24 R_S$</td>
<td>22-27* $R_S$</td>
</tr>
<tr>
<td>Jupiter</td>
<td>20,000</td>
<td>$46 R_J$</td>
<td>$75 R_J$</td>
<td>63-92# $R_J$</td>
</tr>
</tbody>
</table>

Inflated magnetospheres of Jupiter & Saturn due to HOT PLASMAS

Note bimodal average locations
* Achilleos et al. 2008  # Joy et al. 2002
Earth ~ Dipole

\[ R_{mp} \sim (\rho V^2)^{-1/6} \]

solar wind \( \rho V^2 \)

10 \( R_E \)

Jupiter

\[ R_{mp} \sim (\rho V^2)^{-1/3} \]

solar wind \( \rho V^2 \)

100 \( R_J \)
Earth \sim Dipole

\[ R_{mp} \rightarrow 0.7 \ R_{mp} \]

solar wind \( \rho V^2 \)

\boxed{x10 \ Solar \ wind \ pressure}

Jupiter

\[ R_{mp} \rightarrow 0.5 \ R_{mp} \]

solar wind \( \rho V^2 \)

Factor \sim 10 \ variations \ in \ solar \ wind \ pressure \ at \ 5 \ AU

\rightarrow \ observed \ 100-50 \ R_j \ size \ of \ dayside \ magnetosphere
\[ \rho_{sw} V^2_{sw} = \frac{B^2}{2\mu_0} + nkT \]
Dynamics
**Dungey Cycle**

Dynamics at Earth driven by the solar wind coupling the Sun's magnetic field to the Earth's field

- Variable opening & closing rates
- Must be equal over time to conserve magnetic flux
\[ \mathbf{E}_{\text{convection}} = -\zeta \mathbf{V}_{\text{SW}} \times \mathbf{B}_{\text{SW}} \]

\( \zeta \approx \) efficiency of reconnection
\(~10-20\%\)

\( \mathbf{V}_{\text{convection}} \approx \zeta \mathbf{V}_{\text{SW}} \left(\frac{R}{R_{\text{MP}}}\right)^3 \)

(where 3 power assumes a dipole - in reality, the flow is not uniform and the power somewhat less)

(*strictly speaking not convection but advection or circulation)
Solar Wind

Connected to solar wind

Closed magnetic field

Polar view
Reality = Messy & 3D
Dynamics

Dayside magnetopause
- Response to $B_{SW}$ direction
- Solar wind ram pressure

Tail Reconnection
- Depends on recent history of dayside reconnection and state of plasmasheet

Space Weather!
\( V_{co} \sim \Omega \times R \)

\( V_{\text{convection}} \sim \xi V_{SW} (R/R_{MP})^3 \)

Fraction of planetary magnetosphere that is rotation dominated is...

\[
\frac{R_{pp}/R_{MP}}{\sim [r_p R_{MP} \Omega / \xi V_{SW}]^{1/2}} \propto \Omega^{1/2} \mu^{1/6} / (\rho_{SW})^{1/12} V_{SW}^{2/3}
\]

Where \( r_p = \) planetary radius

\( \mu = \) magnetic moment of planet \( B_o R_p^3 \)
\[ V_{\text{co}} \sim \Omega \times R \]

\[ V_{\text{convection}} \sim \zeta V_{\text{SW}} (R/R_{\text{MP}})^3 \]

What if... How would location of plasmapause change?

1. Reconnection more/less efficient at harnessing the solar wind momentum
2. Planet’s spin slows down
3. Planet’s field is stronger
**Solar-wind vs. Rotation-dominated magnetospheres**

\[ \frac{R_{\text{plasmapause}}}{R_{\text{Planet}}} = \]

6.7 \hspace{1cm} 350 \hspace{1cm} 95

**Assumptions:**
1. Planet’s rotation coupled to magnetosphere
2. (Large-scale) Reconnection drives solar wind interaction
Plasma Sources
<table>
<thead>
<tr>
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<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{max}}$ cm$^{-3}$</td>
<td>~1</td>
<td>1-4000</td>
<td>&gt;3000</td>
<td>~100</td>
<td>~3</td>
<td>~2</td>
</tr>
<tr>
<td>Composition</td>
<td>H$^+$</td>
<td>O$^+$ H$^+$ Ionosphere</td>
<td>O$^{n+}$ S$^n$ +</td>
<td>O$^+$ H$_2$O$^+$ H$^+$ Enceladus</td>
<td>H$^+$ Ionosphere</td>
<td>H$^+$ N$^+$ Triton Ionosphere</td>
</tr>
<tr>
<td>Source kg / s</td>
<td>?</td>
<td>5</td>
<td>700-1200</td>
<td>70-200</td>
<td>~0.02</td>
<td>~0.2</td>
</tr>
</tbody>
</table>
Earth Sources of Plasma (5 kg/s):
Solar Wind + ionosphere mixed (over the poles) into magnetotail and convected sunward
Ionosphere: $H^+$ $He^+$ $O^+$
Solar Wind: $H^+$ $He^{++}$

Earth Plasma Flux $5 \text{ kg/s}$

- Polar Wind: Less than 3 eV
- Plasmasphere: Less than 3 eV
- Lobal Wind: 10 - 300 eV
- Warm Plasma Cloak: 10 eV - 3 keV
- Plasma Sheet: 0.5 eV - 5 keV
- Ring Current: 3 - 30 keV

Solar Wind
**Io Plasma torus**

- Total mass 2 Mton
- Source 1 ton/s
- Replaced in 20-50 days
• Strong electrodynamic interaction
• Mega-amp currents between Io and Jupiter

• Plasma interaction with Io's atmosphere
• Heated atmosphere escapes
• ~20% plasma source local
- The magnetic field couples the plasma to the spinning planet.
- Ion gains large gyromotion -> heat.
Cassini UVIS
Andrew Steffl

Spectral diagnosis of plasma conditions Ni, Ne, Te
Plasma Torus   Mass Flux

260-1400 kg/s

- Half lost as fast neutrals -> extended neutral cloud
- Half transported out to plasma disk
Plasma Torus Energy Flux

2 terawatts

40-80% energy from pick up

60-20% energy from hot electrons

70-90% energy radiated in UV

ionization

S 12%
O 7%
S 15%
O 48%

charge exchange

pick-up 82%

52% i-e coupling

coulomb collisions

UV radiation 69%

transport 10%

transport <<1%
In rotating magnetosphere
If fluxtube A contains more mass than B – they interchange

Rayleigh-Taylor instability where centrifugal potential replaces gravity

If $\beta \ll 1$, interchange of A and B does not change field strength.
In rotating magnetosphere
If fluxtube A contains more mass than B – they interchange

You can think of centrifugally-driven fluxtube interchange as a kind of diffusion.
- How will density vary with distance from the source?
- How will diffusion rate depend on gradient of density?
If $\beta \ll 1$, interchange of A and B does not change field strength.

In rotating magnetosphere

If fluxtube A contains more mass than B – they interchange

\[ 10^{35} \quad \text{NL}^2 \quad 10^{36} \]

Inward SLOW

FAST outward

Radial Transport

Jupiter

$R_J$
Aurora
Hubble Space Telescope – Jon Nichols
Jupiter's 3 Types of Aurora

- Steady Main Auroral Oval
- Variable Polar Aurora
- Aurora associated with moons
**Satellite auroral emissions**

- Plasma-moon electrodynamic interaction
- Mega-amp current systems
- Analogous to Earth auroral processes

*Papers by Su, Ergun, Lysak, Hess, Bonfond*
Main Aurora

- Shape constant, fixed in magnetic co-ordinates
- Magnetic anomaly in north
- Steady intensity
- $\sim 1^\circ$ Narrow

Clarke et al., Grodent et al. HST
• As plasma from Io moves outwards its rotation decreases (conservation of angular momentum)

• Sub-corotating plasma pulls back the magnetic field

• Curl $\mathbf{B} \rightarrow$ radial current $J_r$

• $J_r \times \mathbf{B}$ force enforces rotation

Field-aligned currents couple magnetosphere to Jupiter’s rotation

Khurana 2001
Cowley & Bunce 2001
The aurora is the signature of Jupiter’s attempt to spin up its magnetosphere

Outward transport of Iogenic plasma

\( J \) transfers load to ionosphere

Transfer of angular momentum limited by ionospheric conductivity

20-30 R\(_J\)

Cowley et al. 2002

Empirical field + plasma model

Sub-corotating plasmasheet 20-60 R\(_J\)

Knight relation

\( E_\parallel \approx 100 \text{ kV} \)

Upward current \( \approx 1 \mu\text{A/cm}^2 \)

1° narrow auroral oval

Parallel electric fields: potential layers, \( \phi_\parallel \), “double layers”

Downward ???

Upward ~ OK
Where is the clutch slipping?

A - Between deep and upper atmosphere?
B - Between upper atmosphere and ionosphere?
C - Lack of current-carriers in magnetosphere -> $E_{||}$?
Ionosphere - Sets boundary conditions for magnetospheric dynamics
Scale, rotation-dominated, Io source
Main Aurora 20 $R_J$

$R_{MP}$ 60-100 $R_J$

Magnetosheath
Magnetopause
Current Sheet
Magnetotail

Solar wind
1,500,000 km/hr

Bow shock

Io plasma torus
\[ \nabla \times \mathbf{B}_{\text{observed}} \rightarrow \mathbf{J} \]

**Configuration**

**Side View**
- **Expands, stretches field**
- **Plasmasheet**
- **Azimuthal Current** $j_\psi$

**Looking Down**
- **Bends field back**
- **Radial Current** $j_r$

\[ \nabla \cdot \mathbf{J} = 0 \rightarrow \mathbf{J}_\parallel \]
(De-)Coupling - 1

Magnetospheric Factors: $\dot{M}$ $\phi_{\parallel}$

Ionosphere/Thermosphere factors: $\sum_p$ winds, chemistry, heating, radiation, etc;

Communication breaks down $\sim 25R_J$.
Magnetosphere & atmosphere stop talking $> 60R_J$
How does a blob of plasma here communicate with the planet?

How is a stress from the outside communicated to the planet?

How is information transmitted along magnetic field lines?

Alfven waves!
De-Coupling - 2

\[ v_A = \frac{B}{\sqrt{\mu_0 \rho}} \]

Alfven Speed

10^4 km/s
3000 km/s
1000 km/s
300 km/s

Alfven 1-way travel time

Communication breaks down between the planet and magnetosphere

DUSK

90 mins
60 mins
40 mins
120 R_J
95 R_J
60 R_J

Z (R_J)
0 10 20 30 40 50 60
0 5 10 15 20

TIME (Minutes)
0 20 40 60 80 100

RADIAL DISTANCE (R_J)
0 20 40 60 80 100 120
De-Coupling - 3

![Graph showing Alfven Radius relationship with Vr ~ VA and V_Alfven](image)

At ~ 60 R_J

\[ V_{\text{Alfven}} \]

\[ V_r \sim V_A \]

\[ M = \text{nominal} \]
Combining $V_r$ and $V_{azimuthal}$ we get....
• Beyond $\sim 60 \, R_J$ material spirals away from Jupiter in 10s of hours

• Radial transport is still diffusive: Centrifugally-driven fluxtube interchange
Reconnection is reduced in the outer solar system:
- weaker solar fields
- shear boundaries
- strong change in $\beta$

Can small-scale boundary-layer processes act like viscosity?

Shear-driven Kelvin-Helmholtz instability

This is small-scale, intermittent reconnection – as compared to large-scale, quasi-steady reconnection per Dungey cycle
Mass & momentum transport – boundary layers

Upstream IMF

Upstream IMF wrapped around flattened magnetopause
Solar Wind Stresses Overcome Rotation

Add Maxwell stresses from solar wind interaction

Stresses from magnetic shear on boundary
**Vasyliunas Cycle**

Inward in morning

Outward in afternoon

Reconnection sending plasmoids down the tail
Observations of plasmoid events in *Galileo* data.
Solar wind interaction:

- More of a plasma-plasma interaction
- Less of an interaction between magnetic fields
Juno
Spacecraft & Payload

**Orbit Insertion**
4th July 2016

**SPACECRAFT**
Diameter: 66 feet
20 meters

**Power**
400 W

**Spin period**
30 sec

**JunoCam**
camera

**UVS**
UV spectrometer

**Waves**
Radio & plasma

**JIRAM**
IR spectrometer

**Gravity Science**

**JADE**
Low-energy particles

**JEDI**
High-energy particles

**Magnetometer**

**MWR**
Microwaves
**Juno: Close Polar Orbit is Key**

- **Orbit 1**
- **Orbit 16**
- **Orbit 31**

35 polar orbits

- **Duck under radiation belts...**
- **Skim above clouds...**

Perijove (4,200 km above clouds)

Trapped charged particles
Jupiter's Magnetic Field

- Juno's first few passes are showing deviations from previous simple models.
- Hints that the dynamo region is closer to the surface?

![Graphs showing deviations from simple models and hints of a closer dynamo region.](image-url)
In orbit since July 2016!

Polar Magnetosphere

Juno passes directly through auroral field lines

Measures particles precipitating into atmosphere creating aurora

Plasma/radio waves reveal processes responsible for particle acceleration

UV & IR images provides context for *in-situ* observations
Earth Auroral Current Region
Does same physics apply at Jupiter?
Juno UVS

Jupiter's aurora is structured & dynamic
Juno UVS

North

Color ratio -> depth of emission -> energy of precipitation electrons
Earth Based Observing Programs

- Hubble Space Telescope
  - Denis Grodent – Large observing program
- Hisaki UV – Torus, Aurora
- Radio Observations
- Chandra, XMM X-Rays
- Keck, IRTF H$_3^+$
Go Juno!

Thank you!
Uranus

- Highly asymmetric, 
- Highly non-dipolar
- Complex transport (SW + rotation)
- Multiple plasma sources (ionosphere + solar wind + satellites)
Neptune

Similarly complex as Uranus

Zieger et al.
Mercury & Ganymede

Mercury - Magnetic field detected by Mariner 10 in 1974

Ganymede - Magnetic field detected by Galileo in 1996

$B_{\text{surface}} \sim 1/100 \text{ Earth}$
Ganymede

Plasma Flow

X (R_G)

Y (R_G)
Mars

Solar wind

Bow Shock

Magnetic Pile-up Boundary

Photo-electron/Wake Boundary

Ionosphere Escape

Escaping Atmosphere

Tail

Ion Outflow

Precipitating ions

Pick-up Ions
Summary

• Diverse planetary magnetic fields & magnetospheres
• Earth, Mercury, Ganymede magnetospheres driven by reconnection
• Jupiter & Saturn driven by rotation & internal sources of plasma
• Uranus & Neptune are complex – need to be explored!

Stay tuned…. MAVEN mission to Mars

Juno mission to Jupiter!
What's wrong with this picture?


